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TRAFFIC COLLISION AVOIDANCE SYSTEMS (TCAS)

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Abstract: Traffic Collision Avoidance Systems (TCAS) are avionics systems designed to prevent airborne collisions between aircraft. TCAS utilizes a combination of radar, transponder signals, and other data to provide the pilot with a visual and aural warning of nearby aircraft.

Key words : TCAS, radar transponder signals, visual and aural warning

The TCAS operates by continuously scanning the airspace around the aircraft and identifying potential conflicts with other aircraft that are equipped with a transponder. It then provides a warning if there is a risk of collision, and displays commands to the pilot on their cockpit display to avoid the conflicting aircraft.

There are two types of TCAS systems: TCAS I and TCAS II. TCAS I provides a basic level of protection and is required on all aircraft with a maximum takeoff weight greater than 33,000 pounds. TCAS II provides a higher level of protection and is required on all aircraft with a maximum takeoff weight greater than 60,000 pounds, as well as on certain other aircraft operating in high-density airspace.

Picture 1: *TCAS indicator*

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System description

TCAS involves communication between all aircraft equipped with an appropriate transponder (provided the transponder is enabled and set up properly). Each TCAS-equipped aircraft interrogates all other aircraft in a determined range about their position (via the 1030 MHz radio frequency), and all other aircraft reply to other interrogations (via 1090 MHz). This interrogation-and-response cycle may occur several times per second.

The TCAS system builds a three dimensional map of aircraft in the airspace, incorporating their range (garnered from the interrogation and response round trip time), altitude (as reported by the interrogated aircraft), and bearing (by the directional antenna from the response). Then, by extrapolating current range and altitude difference to anticipated future values, it determines if a potential collision threat exists.

TCAS and its variants are only able to interact with aircraft that have a correctly operating mode C or mode S transponder. A unique 24-bit identifier is assigned to each aircraft that has a mode S transponder.

The next step beyond identifying potential collisions is automatically negotiating a mutual avoidance manoeuver (currently, manoeuvers are restricted to changes in altitude and modification of climb/sink rates) between the two (or more) conflicting aircraft. These avoidance manoeuvers are communicated to the flight crew by a cockpit display and by synthesized voice instructions.

A protected volume of airspace surrounds each TCAS equipped aircraft. The size of the protected volume depends on the altitude, speed, and heading of the aircraft involved in the encounter. The illustration below gives an example of a typical TCAS protection volume.

Impetus for a system and history

Research into collision avoidance systems has been ongoing since at least the 1950s, and the airline industry has been working with the Air Transport Association of America (ATA) since 1955 toward a collision avoidance system. ICAO and aviation authorities such as the Federal Aviation Administration were spurred into action by the 1956 Grand Canyon mid-air collision.

It was not until the mid-1970s, however, that research centered on using signals from ATCRBS airborne transponders as the cooperative element of a collision avoidance system. This technical approach allows a collision avoidance capability on the flight deck, which is independent of the ground system. In 1981, the FAA announced a decision to implement an aircraft collision avoidance concept called the Traffic Alert and Collision Avoidance System (TCAS). The concept is based upon agency and industry development efforts in the areas of beacon based collision avoidance systems and air-to-air discrete address communications techniques utilizing Mode S airborne transponder message formats.

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A short time later, prototypes of TCAS II were installed on two Piedmont Airlines Boeing 727 aircraft, and were flown on regularly scheduled flights. Although the displays were located outside the view of the flight crew and seen only by trained observers, these tests did provide valuable information on the frequency and circumstances of alerts and their potential for interaction with the ATC system. On a follow-on phase II program, a later version of TCAS II was installed on a single Piedmont Airlines Boeing 727, and the system was certified in April 1986, then subsequently approved for operational evaluation in early 1987. Since the equipment was not developed to full standards, the system was only operated in visual meteorological conditions (VMC). Although the flight crew operated the system, the evaluation was primarily for the purpose of data collection and its correlation with flight crew and observer observation and response.

Later versions of TCAS II manufactured by Bendix/King Air Transport Avionics Division were installed and approved on United Airlines airplanes in early 1988. Similar units manufactured by Honeywell were installed and approved on Northwest Airlines airplanes in late 1988. This limited installation program operated TCAS II units approved for operation as a full-time system in both visual and instrument meteorological conditions (IMC) on three different aircraft types. The operational evaluation programs continued through 1988 to validate the operational suitability of the systems.

Incidents

The implementation of TCAS added a safety barrier to help prevent mid-air collisions. However, further study, refinements, training and regulatory measures were still required because the limitations and misuse of the system still resulted in other incidents and fatal accidents which include the:

1996 Charkhi Dadri mid-air collision accident over New Delhi;

1999 Lambourne near-collision, involving a Boeing 737-300 and a Gulfstream IV. The airspace above Lambourne is the waiting zone for Heathrow. The event is notable as both planes entered the zone from different directions leading to an imminent head-on collision (one o'clock position). The traffic advisory (amber mark) did almost immediately turn into a resolution advisory (red mark) with a projected time for collision of less than 25 seconds.

2001 Japan Airlines mid-air incident; where the Captain of Japan Airlines Flight 907 (a Boeing 747-400), 40-year old Makoto Watanabe Watanabe Makoto), chose to descend, ordered by the air traffic controller, when TCAS told the flight crew to climb, nearly colliding with the descending JAL F958 DC-10 en route from Busan to Tokyo's Narita Airport.

2002 Überlingen mid-air collision, between a Boeing 757 and a Tupolev Tu-154, where the Tupolev pilots declined to follow their TCAS resolution advisory (RA), instead following the directions of the air traffic controller, while the Boeing pilots followed their TCAS-RA, having no ATC instruction.

2006 collision between Gol Transportes Aéreos Flight 1907 (a Boeing 737) and an Embraer Legacy 600; the Embraer's transponder had inadvertently been switched off, disabling its own TCAS and rendering the plane invisible to the TCAS on board flight 1907.

2011 Fribourg near-collision, involving Germanwings Airbus A319 Flight 2529 and Hahn-Air-Lines Raytheon Premier I Flight 201. Air traffic control at Geneva allowed flight 2529 to sink to flight level 250 but entered flight level 280 as usual for handover to traffic control at Zurich. Air traffic control at Zurich allowed flight 201 to climb to flight level 270. This triggered a resolution advisory (RA) for the Airbus to sink and for the Raytheon to climb which was followed by both aircraft. Nine seconds later Geneva instructed the Raytheon to sink to flight level 260 which they then followed. It led to a situation where both planes passed at 30 metres (100 ft) minimum distance. Shortly later the Raytheon was lower than the Airbus and TCAS issued a reversal RA for the Airbus to climb and for the Raytheon to sink.

2019 near collision between a Boeing 777-328(ER) and an Airbus A320-232 over Mumbai airspace. The Boeing AF 253 operated by Air France was flying from Ho Chi Minh City to Paris at a FL 320 while the Airbus EY 290 operated by Etihad Airways was flying from Abu Dhabi to Kathmandu at FL 310. After a TCAS activation the ATC ordered the Etihad to climb to FL330.

System components

A TCAS installation consists of the following components:

TCAS computer unit

Performs airspace surveillance, intruder tracking, its own aircraft altitude tracking, threat detection, resolution advisory (RA) manoeuvre determination and selection, and generation of advisories. The TCAS Processor uses pressure altitude, radar altitude, and discrete aircraft status inputs from its own aircraft to control the collision avoidance logic parameters that determine the protection volume around the TCAS aircraft.

Antennas

The antennas used by TCAS II include a directional antenna that is mounted on the top of the aircraft and either an omnidirectional or a directional antenna mounted on the bottom of the aircraft. Most installations use the optional directional antenna on the bottom of the aircraft. In addition to the two TCAS antennas, two antennas are also required for the Mode S transponder. One antenna is mounted on the top of the aircraft while the other is mounted on the bottom. These antennas enable the Mode S transponder to receive interrogations at 1030 MHz and reply to the received interrogations at 1090 MHz.

Cockpit presentation

The TCAS interface with the pilots is provided by two displays: the traffic display and the RA display. These two displays can be implemented in a number of ways including displays that incorporate both displays into a single, physical unit. Regardless of the implementation, the information displayed is identical. The standards for both the traffic display and the RA display are defined in DO-185A.

Operation modes

TCAS II can be currently operated in the following modes:

Stand-by

Power is applied to the TCAS Processor and the mode S transponder, but TCAS does not issue any interrogations and the transponder will reply to only discrete interrogations.

Transponder

The mode S transponder is fully operational and will reply to all appropriate ground and TCAS interrogations. TCAS remains in stand-by.

Traffic advisories only

The mode S transponder is fully operational. TCAS will operate normally and issue the appropriate interrogations and perform all tracking functions. However, TCAS will only issue traffic advisories (TA), and the resolution advisories (RA) will be inhibited.

Automatic (traffic/resolution advisories)

The mode S transponder is fully operational. TCAS will operate normally and issue the appropriate interrogations and perform all tracking functions. TCAS will issue traffic advisories (TA) and resolution advisories (RA), when appropriate.

TCAS works in a coordinated manner, so when an RA is issued to conflicting aircraft, a required action (i.e., Climb. Climb.) has to be immediately performed by one of the aircraft, while the other one receives a similar RA in the opposite direction

Alerts

TCAS II issues the following types of aural annunciations:

--- Traffic advisory (TA)
--- Resolution advisory (RA)
--- Clear of conflict

When a TA is issued, pilots are instructed to initiate a visual search for the traffic causing the TA. If the traffic is visually acquired, pilots are instructed to maintain visual separation from the traffic. Training programs also indicate that no horizontal maneuvers are to be made based solely on information shown on the traffic display.

Slight adjustments in vertical speed while climbing or descending, or slight adjustments in airspeed while still complying with the ATC clearance are acceptable.

When an RA is issued, pilots are expected to respond immediately to the RA unless doing so would jeopardize the safe operation of the flight. This means that aircraft will at times have to manoeuver contrary to ATC instructions or disregard ATC instructions. In these cases, the controller is no longer responsible for separation of the aircraft involved in the RA until the conflict is terminated.

On the other hand, ATC can potentially interfere with a pilot's response to RAs. If a conflicting ATC instruction coincides with an RA, a pilot may assume that ATC is fully aware of the situation and is providing the better resolution. But in reality, ATC is not aware of the RA until the RA is reported by the pilot. Once the RA is reported by the pilot, ATC is required not to attempt to modify the flight path of the aircraft involved in the encounter. Hence, the pilot is expected to "follow the RA" but in practice this does not always happen.

Some countries have implemented "RA downlink" which provides air traffic controllers with information about RAs posted in the cockpit. Currently, there are no ICAO provisions concerning the use of RA downlink by air traffic controllers.

The following points receive emphasis during pilot training:

--- Do not manoeuver in a direction opposite to that indicated by the RA because this may result in a collision.

--- Inform the controller of the RA as soon as permitted by flight crew workload after responding to the RA. There is no requirement to make this notification prior to initiating the RA response.

--- Be alert for the removal of RAs or the weakening of RAs so that deviations from a cleared altitude are minimized.

--- If possible, comply with the controller's clearance, e.g. turn to intercept an airway or localizer, at the same time as responding to an RA.

--- When the RA event is completed, promptly return to the previous ATC clearance or instruction or comply with a revised ATC clearance or instruction.

Safety aspects

Safety studies on TCAS estimate that the system improves safety in the airspace by a factor of between 3 and 5.

However, it is well understood that part of the remaining risk is that TCAS may induce midair collisions: "In particular, it is dependent on the accuracy of the threat aircraft's reported altitude and on the expectation that the threat aircraft will not make an abrupt maneuver that defeats the TCAS Resolution Advisory (RA). The safety study also shows that TCAS II will induce some critical near midair collisions.).

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One potential problem with TCAS II is the possibility that a recommended avoidance maneuver might direct the flight crew to descend toward terrain below a safe altitude. Recent requirements for incorporation of ground proximity mitigate this risk. Ground proximity warning alerts have priority in the cockpit over TCAS alerts.

Some pilots have been unsure how to act when their aircraft was requested to climb whilst flying at their maximum altitude. The accepted procedure is to follow the climb RA as best as possible, temporarily trading speed for height. The climb RA should quickly finish. In the event of a stall warning, the stall warning would take priority.

Both cases have been addressed by Version 7.0 of TCAS II and are currently handled by a corrective RA together with a visual indication of a green arc in the IVSI display to indicate the safe range for the climb or descent rate. However, it has been found that in some cases these indications could lead to a dangerous situation for the involved aircraft. For example, if a TCAS event occurs when two aircraft are descending one over the other for landing, the aircraft at the lower altitude will first receive a "Descend, descend" RA, and when reaching an extreme low altitude, this will change to a "Level off, level off" RA, together with a green arc indication directing the pilot to level off the aircraft. This could place the aircraft dangerously into the path of the intruder above, who is descending to land. A change proposal has been issued to correct this problem.

Catastrophe as a consequence of confusion

TCAS is not a perfect system. In 2002, a Tupolev Tu-154 and a Boeing 757F collided over Überlingen, Germany, resulting in the deaths of all 71 occupants of the two aircraft. The cause of the crash was found to have been confusion between the instructions provided by air traffic control and TCAS.

Specifically, the Tupolev's crew disregarded TCAS instructions in favor of those from local air traffic control. Meanwhile, the Boeing's crew followed TCAS advice, having not been instructed by ATC. As such, both aircraft descended (rather than one descending and one climbing as per TCAS) and subsequently collided. The crash was the second-deadliest mid-air collision of the 21st century, behind GOL flight 1907. This flight, operated by a Boeing 737, collided with an Embraer Legacy private jet over Brazil in September 2006. The latter of these aircraft did not have its transponder activated at the time of the crash, rendering it invisible to the GOL 737's TCAS. All 154 occupants of the 737 lost their lives, although the Embraer was able to land safely despite the damage, with no injuries to its seven occupants.

An incident that could have been avoided

On November 12th, 1996, the world’s deadliest mid-air collision took place near India’s capital New Delhi. A Saudia Boeing 747 had departed Delhi while a Kazakhstan Airlines Ilyushin Il-76TD was descending to land in the capital city. The

Saudia aircraft was given permission by the ATC to climb to 14,000 feet, while the incoming Kazakhstan plane was cleared to descend to 15,000 feet. The controllers believed that both planes would pass each other safely due to a 1,000 feet separation between them. But moments later, the two aircraft collided as they entered a thick cloud, killing all 349 people onboard. A post-crash investigation suggested that the Kazhak pilots failed to understand the ATC instructions and descended below their assigned altitude.

In the wake of the incident, the Indian aviation authorities made it mandatory for all aircraft being operated in its airspace to be equipped with TCAS.

While the advantage of using TCAS is undeniable, this system has a number of significant limitations:

TCAS can only issue vertical separation instructions.

The air traffic control system does not receive instructions issued by TCAS to ships, so air traffic controllers may not be aware of such instructions, and even give conflicting instructions, which causes crew confusion (collision over Lake Constance on July 1, 2002).

For effective operation of TCAS, it is necessary that all aircraft be equipped with this system, since aircraft detect each other by transponders.

Plane crashes

The collision over Lake Constance on July 1, 2002 occurred due to conflicting instructions from TCAS and the controller: the crew of one of the aircraft followed the instructions of TCAS, the crew of the other - the instructions of the controller Peter Nielsen, which diverged from the instructions of TCAS. These mistakes not only led to the plane crash, but indirectly, on February 24, 2004, they led to the murder of Peter Nielsen himself by Vitaly Kaloev, whose family died in the crash.

Current limitations

While the safety benefits of current TCAS implementations are self-evident, the full technical and operational potential of TCAS is not fully exploited due to limitations in current implementations (most of which will need to be addressed in order to further facilitate the design and implementation of Free flight) and NextGen:

Most TCAS II issues reported to the Aviation Safety Reporting System (ASRS) encompass anomalous or erroneous operation of TCAS II equipment, TCAS-induced distraction, airborne conflicts provoked by TCAS, and non-standard use of TCAS.

Like a controller, TCAS II uses Mode C information to determine vertical separation on other traffic. Should Mode C even temporarily provide erroneous altitude information, an erroneous Resolution Advisory command to climb or descend may result. Unlike a controller, TCAS II cannot query the flight crew to determine if the problem lies with malfunctioning equipment.

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Pilots frequently cite TCAS II related auditory and workload interference with normal cockpit duties. Many TCAS incident reports received at the ASRS allege that pilot response to erroneous TCAS commands has promoted a conflict where, initially, none existed. Consider the following near mid-air collision (NMAC) where the TCAS II RA may well have been triggered by the high climb rate of air carrier (Y). TCAS is limited to supporting only vertical separation advisories, more complex traffic conflict scenarios may however be more easily and efficiently remedied by also making use of lateral resolution maneuvers; this applies in particular to traffic conflicts with marginal terrain clearance, or conflict scenarios that are similarly restricted by vertical constraints (e.g. in busy RVSM airspace)

ATC can be automatically informed about resolution advisories issued by TCAS only when the aircraft is within an area covered by a Mode S, or an ADS-B monitoring network. In other cases controllers may be unaware of TCAS-based resolution advisories or even issue conflicting instructions (unless ATC is explicitly informed by cockpit crew members about an issued RA during a high-workload situation), which may be a source of confusion for the affected crews while additionally also increasing pilot work load. In May 2009, Luxembourg, Hungary and the Czech Republic show downlinked RAs to controllers.

In the above context, TCAS lacks automated facilities to enable pilots to easily report and acknowledge reception of a (mandatory) RA to ATC (and intention to comply with it), so that voice radio is currently the only option to do so, which however additionally increases pilot and ATC workload, as well as frequency congestion during critical situations.

In the same context, situational awareness of ATC depends on exact information about aircraft maneuvering, especially during conflict scenarios that may possibly cause or contribute to new conflicts by deviating from planned routing, so automatically visualizing issued resolution advisories and recalculating the traffic situation within the affected sector would obviously help ATC in updating and maintaining situational awareness even during unplanned, ad hoc routing changes induced by separation conflicts.

Today's TCAS displays do not provide information about resolution advisories issued to other (conflicting) aircraft, while resolution advisories issued to other aircraft may seem irrelevant to another aircraft, this information would enable and help crews to assess whether other aircraft (conflicting traffic) actually comply with RAs by comparing the actual rate of (altitude) change with the requested rate of change (which could be done automatically and visualized accordingly by modern avionics), thereby providing crucial realtime information for situational awareness during highly critical situations.

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